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Performance Evaluation of MAC Layer Protocol over Wireless Body Area Sensor Networks

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Abstract

This article explores the intricacies of the ZigBee wireless protocol that works on the underlying IEEE 802.15.4 standard in order to fine-tune it in a way that will meet the unique requirements of a Wireless Body Sensor Network. This particular standard is relatively new and is specifically designed to offer low cost and power consumption, reliability, and inter-operability for sensor and control applications with low to moderate data rates. By simulating ZigBee wireless networks with the possible star, tree, or mesh topologies under different scenarios, the performance of each topology can be evaluated and assessed. The results from the simulations demonstrate that ZigBee wireless networks using the mesh topology have the highest overall performance regardless of the number of nodes. Moreover, the ratio of routers to end-devices in a Personal Area Network can either improve or deteriorate its performance.

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1. Introduction

Recently, devices using sensor technology for the purpose of control and monitoring are widely used in multiple fields. In particular, wired sensors are gradually being replaced by wireless technologies due to outstanding developments in the fields of microelectronics, radio and communications [1][2]. Therefore, wireless sensor networks have stimulated many research concerns about the use of designed wireless technology so far, such as Bluetooth, WiFi, Zigbee and LoRa. Among them, Bluetooth and WiFi mainly focus on the ability to support higher data rates and wider range of activities. This results in power consumption requirements, cost and feasibility factors [3]. Designed based on standard Personal Area Network (PAN) IEEE 802.15.4, ZigBee has been widely applied in various fields, e.g., large-scale automation and intelligent control systems, and are gradually replacing the existing non-standard technologies. Similar to Long Range (LoRa) wireless radio frequency (RF) technology, ZigBee is characterized by low power consumption, low cost, and low data rates. Although the communication distance of Zigbee is shorter than that of LoRa, Zigbee has more outstanding advantages over LoRa in terms of the ability to configure multiple network topologies as well as to route multi-cast information transmission [4][5].

Wireless Body Sensor Network (WBSN), which is a type of PAN, is based on IEEE 802.15.4 standard with increasing attention. WBSN is a network that monitors human body signals such as body temperature, blood pressure, and heart rate in real time. Among multiple wireless technologies, Zigbee is the preferred standard for WBSN due to the nature of physical and MAC layers of IEEE 802.15.4 to ensure the wireless network standards and meet the special nature of the sensors and controls [6].

Up to now, few accurate simulations and implementations have been done for ZigBee protocol. It is known that OPNET is one of the most popular and powerful in network modeling and simulation environment [7][8][9]. Two IEEE802.14.5 OPNET simulation models have been studied and launched. In addition, the National Institute of Standards and Technology (NIST) has published the first model [10], but with only the physical layer and the data link layer and a few functions of the network layer in the Open System Interconnection (OSI) stack. Moreover, instead of using the accurate OPNET wireless library, the NIST

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uses its own radio channel model and only supports un-slotted CSMA/CA MAC protocols. In comparison with NIST simulation model, the model developed by the investigation of ZigBee protocol is conducted mainly through individual research using the OPNET Modeler 16.0. From various sources and documentations, the combination of OPNET and Zigbee can support full layers with power module added [11]. Since the OPNET-Zigbee simulation model provides more features and uses the accurate OPNET wireless library, this model has been used to find out the performance evaluation of MAC layer protocol over WBSN.

Last but not least, just a few of the reports have studied the impact of node-density on quality of service (QoS) of ZigBee sensor network. In this paper, it is critical to have an analytical model configured under different network schemes such as node-density, end-to-end delay, throughput, PAN load of ZigBee sensor network [12][13]. All simulation results from OPNET are collected and classified to illustrate the final simulation results.

The rest of this paper is organized as follows. Section 2 introduces the general concept of IEEE802.15.4 protocol and covers some relevant features of this protocol. In Section 3, we further explain the simulation models and simulation environment setup. Section 4 shows the simulation scenarios and discusses the simulation results. Finally, we conclude the paper in Section 5.

2. Review of IEEE802.15.4 protocol

While the IEEE802.15.4 standard is classified in the Low-Rate Wireless Personal Area Networks (LR-WPAs) [14] specified by the physical layer and MAC sub-layer, the ZigBee standard is developed based on the IEEE802.15.4 with the network and application layers added [15][16]. According to [15], three different types of nodes exist in a wireless sensor network: the coordinator, the router, and the end device. The coordinator acts as the root of a network to instantiate the network format and exchange all the information about the nodes in the branches for communications. And thus, only one coordinator is needed in each local area network. Unlike the coordinator, the routers are located on the routing path given by a routing table. And any messages are easy to be passed through multi-hop routing. Both the coordinator and the routers are called Full Function Devices (FFDs). End devices, so-called Reduced Function Devices (RDFs), are only responsible for receiving data from the sensors and sending them to the FFDs.

2.1. IEEE802.15.4 Physical and MAC Layers

Following the OSI model, the physical layer is equipped with radio interfaces which are responsible for data transmission and reception. The IEEE802.15.4 is currently operating in three frequency bands (Table 1), i.e., a data rate of 20kbps at the license 868MHz band in Europe, 40kbps at the license 915MHz band in the North America, and 250 kbps at the ISM 2.4GHz band worldwide [15].

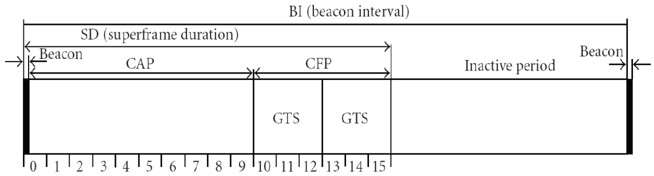


Figure 1. Frame structure of the beacon signal [15].

Two operation modes including beacon-enabled mode and non-beacon-enabled mode are handled by the Medium Access Control (MAC) protocol. The coordinator manages the modes for the network. Moreover, in the beacon-enabled mode, the PAN coordinator periodically generates the beacon frames to all local branches to synchronize the devices and broadcast its PAN identification. As shown in Fig. 1, super-frame is created in the cycle of beacon frame. Super-frame structure is generated by the coordinator to communicate with the end devices associated with the right PAN. Each super-frame contains an active period section and an optional inactive period section. Because each super-frame is covered by a beacon frame, the Beacon Interval (BI) is the time between two consecutive beacon frames.

There are 16 time slots in the active period section, namely the Super-Frame Duration (SD). Data can be transmitted during these time slots. The Beacon Order (BO) and the Super-Frame Order (SO) are two parameters determining the BI and the SD values given as below

$$\begin{aligned} BI &= aBaseSuperFrameDuration \times 2^{BO}, \\ SD &= aBaseSuperFrameDuration \times 2^{SO}, \end{aligned} \quad (1)$$

where $0 \leq SO \leq BO \leq 14$.

In Eq. (1), the SD refers to the minimum duration of the super-frame. This duration is 15.36ms if the assumption of 250kbps in the 2.4GHz frequency band is made [10]. Moreover, as shown in Fig. 1, each active period can be further divided into a Contention Access Period (CAP) and an optional Contention Free Period (CFP). Within the CAP, Slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) is used to handle the priority access arbitration.

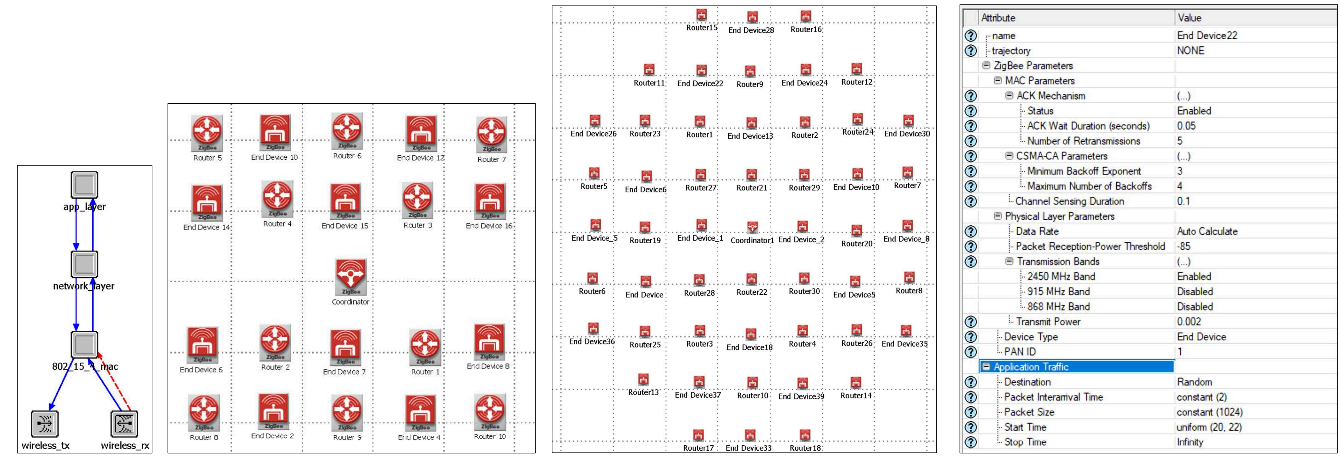
The CFP is activated when a device sends a request to the PAN coordinator. Upon receiving the request, the PAN coordinator checks whether there are sufficient resources to allocate the requested time slots or not. These slots are referred to as Guaranteed Time Slots (GTS).

In non-beacon enabled mode, the un-slotted CSMA/CA mechanism is used instead of the super-frame structure. Therefore, the GTS is not provided by the non-beacon-enabled mode. For this reason, this paper focuses on the beacon-enabled mode because this operation mode is flexible for WBAN applications.

In beacon-enabled mode during the CAP, the slotted CSMA/CA algorithm is based on a basic time unit of the MAC protocol called Back-off Period (BP). There are three

Table 1. ZigBee physical layer specifications.

Attribute	2450MHz band	915MHz band	868MHz band
Maximum data rate	250 kbps	40 kbps	20 kbps
Number of Channel	16	10	1
Type of modulation	QPSK	BPSK	BPSK
Chip pseudo-noise sequence	32	15	15
Bit per symbol	4	1	1
Symbol period	$16\mu s$	$24\mu s$	$49\mu s$
Multiple access	DSSS	DSSS	DSSS



(a) The ZigBee node model stack. (b) Scenario 1 network architecture with 20 nodes. (c) Scenario 2 network architecture with 50 nodes. (d) Zigbee node configuration.

Figure 2. Network simulation and Zigbee node configuration.

parameters in the slotted CSMA/CA mechanism, i.e., the Back-off Exponent (BE), the Contention Window (CW), and the Number of Back-offs (NB). A random variable between 0 and $(2^{BE} - 1)$ is used to compute the back-off delay for the BE. A number of back-off periods are called the CW. And the NB is a counter of back-off requirement while trying to access the channel.

2.2. Network Layer

The network layer provides a lot of functions such as joining/leaving of a network, route discovery, multi-hop routing and security [16]. Multiple network topologies are supported in order to accommodate the numerous requirements of different unique applications.

The star topology is a simple network architecture where there exists only one PAN coordinator. All the other devices are end-devices and they communicate directly to the PAN coordinator. Applications that benefit from this topology include home automation, personal computer (PC) peripherals, toys, and games [5]. Similarly, the tree topology has only one PAN coordinator in the network. However, in addition to the end-devices, the FFDs acting as routers may also connect to the tree network as a leaf node at the end of a branch. The routers at the edge of branches coordinate and provide synchronization services to the connected end-devices and coordinator. In mesh topology, there is also only one PAN coordinator. It differs from the tree topology that any FFD can act as a coordinator or a router and communicate with each other as long as they are in the transmission range. The range of applications that can benefit from such a network extends from industrial (control and monitoring) to small personal wireless sensor networks.

2.3. Application Layer

The application layer consists of the Application Support (APS) sub-layer, the ZigBee Device Objects (ZDO), and the client-defined Application Objects (APO). The APS sub-layer is responsible for pairing devices together based on their respective services and needs. Additionally, it offers data transferring, i.e., message-forwarding services for the APOs and the ZDO. The client-defined APOs are software (from application developers) that implements the actual applications and enables the devices to operate according to the ZigBee-defined application descriptions. Each APO is identified by a locally unique number that other APOs can use as an extension to the network device address to interact with it [4]. Finally, the responsibilities of the ZDO include defining the role of each device within the network, e.g., PAN coordinator, router, or end-device, as well as establishing and maintaining a secure connection between network devices.

3. OPNET Modeler

To evaluate the performance of ZigBee protocol and IEEE 802.15.4 standard in PAN, we use the simulation tool named OPNET Modeler 16.0 which is the most popular tool to design and analyze the protocols, devices, networks and applications.

Zigbee Node Model: A discrete event simulation model and the ZigBee model suite in the OPNET Modeler are used to analyze the network performance of ZigBee PANs. In the OPNET documentation of ZigBee model, some functions such as security, multicast traffic, indirect transmission have not been implemented yet. However, the lack of these functions does not affect the system performance evaluation. As shown in Fig. 2(a), the ZigBee node model includes 4 processes that illustrate the activities of application layer, network layer, MAC layer and wireless transceiver.

Application Process Model: Although the application layer in the model does not provide all the functionalities that the ZigBee protocol specifies, it does offer several critical functions. These functions include the ability for devices to discover the networks and join them, as well as generate and receive the application traffic. The detection of failure and the recovery of failed ZigBee devices are also available. Figure 2(d) shows a list of attributes that are configurable in this layer.

Network Process Model: The network layer of this model enables all the basic functionalities that the ZigBee protocol specifies. In addition, it allows the construction and simulation of the star, mesh and tree routing processes.

MAC Process Model: The full functionalities of the IEEE 802.15.4 MAC layer are provided by OPNET in this model. The model also supports the unslotted CSMA/CA mechanism for networks running under the non-beacon mode. Figure 2(d) shows a list of configurable attributes enabled in this layer, while Fig. 3 is a screen-shot of the MAC process model itself, as seen in the OPNET simulator.

4. Performance Evaluation

In this section, we analyze the performance of ZigBee protocol by constructing different scenarios operating under the star, tree and mesh network topologies. By comparing the performance statistics and setbacks of each model, we determine which topology offers the highest performance and is mostly suitable for WBSN. Furthermore, since the tree and mesh topologies allow FFDs to act as the routers to pass on

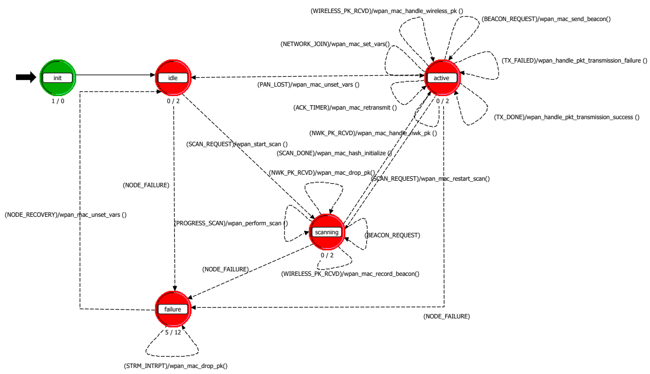


Figure 3. IEEE 802.15.4 MAC process model.

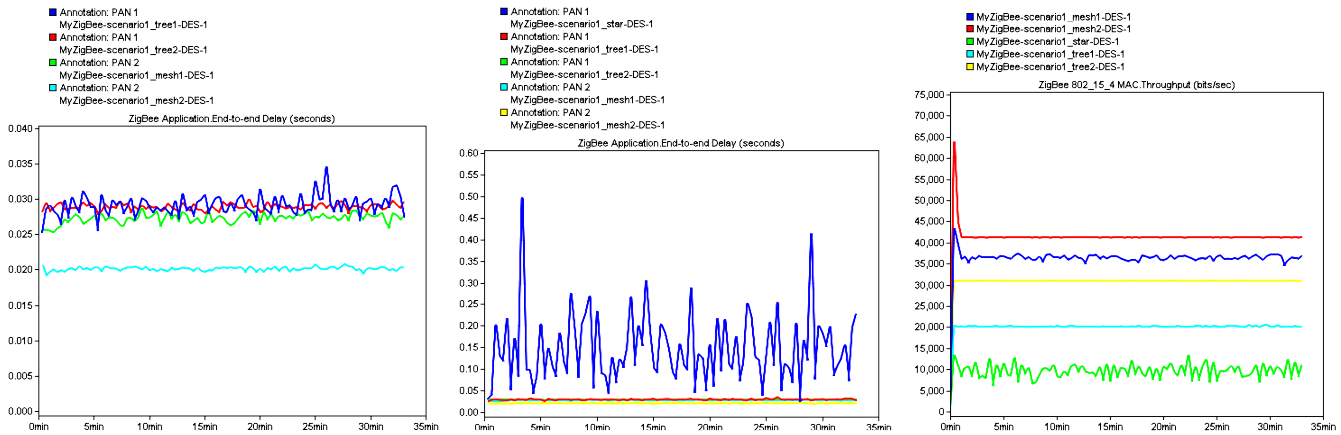
Table 2. Two scenarios for the network simulation.

Scenarios	Star	Tree	Mesh
20 nodes	Coordinator, 20 end-devices	Coordinator	Coordinator
		Case 1: 4 routers, 16 end-devices	Case 1: 4 routers, 16 end-devices
		Case 2: 10 routers, 10 end-devices	Case 2: 10 routers, 10 end-devices.
50 nodes	Coordinator, 50 end-devices	Coordinator	Coordinator
		Case 1: 10 routers, 40 end-devices	Case 1: 10 routers, 40 end-devices
		Case 2: 30 routers, 20 end-devices	Case 2: 30 routers, 20 end-devices

the network information to the other nodes, it is obvious that different amount of routers will give different results. As such, for these two topologies, there will be separated cases in each of the scenarios to verify this speculation. The restrictions for constructing the star, tree, and mesh topologies in the model, as per the documentation in the OPNET tutorial, are given as follows.

- Star Topology - One coordinator node and the desired number of router and end devices in the workspace. On each device, the Network Parameter attribute is set to Default Star Network.

- Tree Topology - One coordinator node and the desired number of router and end devices in the workspace. On each device, the Network Parameter attribute is set to



(a) End-to-End delay in second

(b) ETE delay for the tree and mesh topologies in second

(c) Throughput in bit/s

Figure 4. Set of results from scenario 1 with 20 nodes.

Default Tree Network. Each router can accommodate about two end devices.

- Mesh Topology - One coordinator node and the desired number of router and end devices in the workspace. On each device, the Network Parameter attribute is set to Default Mesh Network.

Each of the network scenarios will comprise one PAN coordinator node accompanied by a number of routers and end-devices, depending on the topology. Every node in all the networks will be set to begin transmitting traffic messages to a random destination (about 20 seconds) into the simulation. All the simulations will run within 2000 simulation seconds. The scenarios for which the network topologies will be assessed are described in Table 2.

As briefly outlined in the previous section, there are two scenarios evaluated under the three available network topologies. Simulations running under the tree and mesh topologies have two separated cases, where they differ only by the number of routers assigned to each PAN.

4.1. Simulation Scenarios

In the first scenario as shown in Fig. 2(b), we imitate a simple wireless PAN consisting of 1 coordinator and 20 routers or end-devices, depending on the topology. This should provide a decent overview of how well a small ZigBee network performs. In the second scenario as shown in Fig. 2(c), a larger network with a denser concentration of nodes is constructed. This PAN consists of 1 coordinator and 50 other devices. The larger amount of nodes, and therefore traffic produced, cause throughput and end-to-end (ETE) delay significantly larger than the previous scenarios do.

4.2. Simulation Results

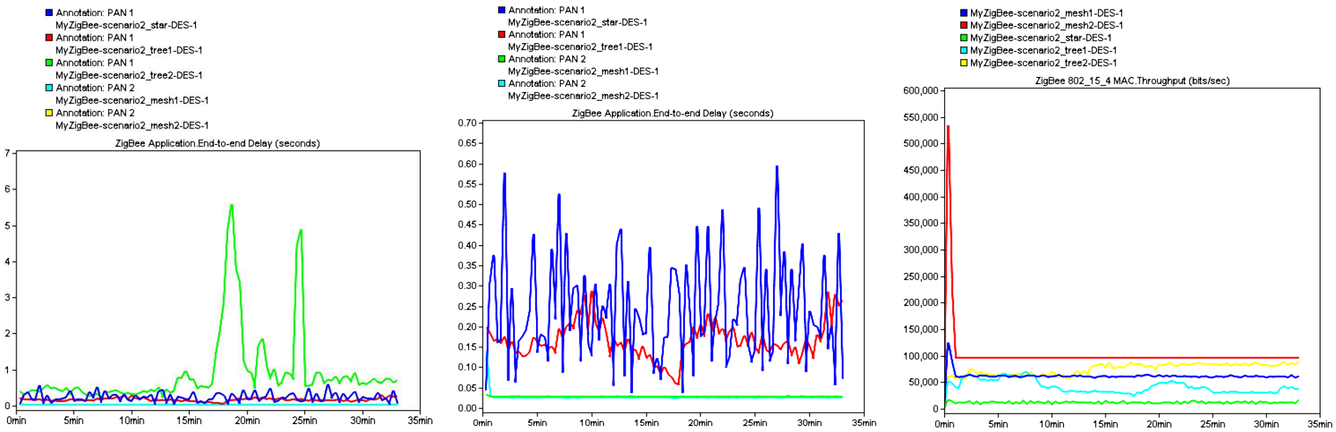
This section will present the simulation results gathered regarding the two scenarios. The primary performance metrics of interest are the average ETE delay, throughput (bits/sec), and the MAC load. The average ETE delay measures the total time needed for one packet to be created from a source node and received at its destination. The throughput is a measurement of how many bits of information are able to transmit through the network per second. Finally, the MAC load determines how heavy the traffic load is, and how much work is done.

Results from 20 nodes scenario. From Fig. 4(a), it is obvious that the star topology yields the longest ETE delay, while the performance of the tree and mesh topologies are relatively similar to the two mesh arrangements performing just a little better. The reason of the star network is performing comparatively weaker than the other two networks is that the lone coordinator is assigned to do every operation of routing information throughout the whole network.

A closer look at the performances of the tree and mesh networks is given in Fig. 4(b). The results show that consisting of a larger number of routers than end-devices, MyZigBee-scenario1-mesh2 has the lowest ETE delay in comparison. Meanwhile, the other three networks give a generally similar scale of performance, with the other mesh network just slightly faster in transmitting information from node to node.

As can be seen from the Fig. 4(c), the star arrangement has a significantly lower throughput than the tree and mesh counterparts do. It is not surprising to observe that the mesh networks are capable of higher throughput than the tree networks since every node can act as a router and hold general network information. Also, it is interesting to note that MyZigBee-scenario1-tree2 and MyZigBee-scenario1-mesh2, which contain a dense number of routers in their networks, are experiencing higher throughput than their counterparts which contain a significantly smaller number of routers.

All results illustrated in Fig. 4 indicate that a higher number of routers in a network produce a higher traffic load upon the



(a) End-to-End delay in second

(b) ETE delay without ZigBeescenario2_tree2 in second

(c) Throughput in bit/s

Figure 5. Set of results from scenario 2 with 50 nodes.

PAN. This is because the routers typically generate a higher load than end-devices for relaying information from source nodes to destination nodes.

Results from 50 nodes scenario. In this scenario, the results of ETE delay are shown in Fig. 5 for all the cases and in comparison to each other. The anomaly occurred in the second case of the tree topology setting seems to indicate that during that time, there are packets traversing long distances to reach their destinations. As such, we suspect the reason being the excessive number of routers caused the routing algorithm in the network to be distorted. In order to properly evaluate this scenario, we omit the tree2 network.

From Fig. 5(a), we can see that the star topology performs the poorest result. Performing just slightly better is the tree topology, which contradicts the results from scenario one where it is significantly better. This implies that the performance declines in a larger tree topology network. One reason for the decline in performance is because the key nodes become congested with traffic and as a result causing a slowdown in the overall system. Finally, it can be observed that the two mesh networks have a significantly lower ETE delay.

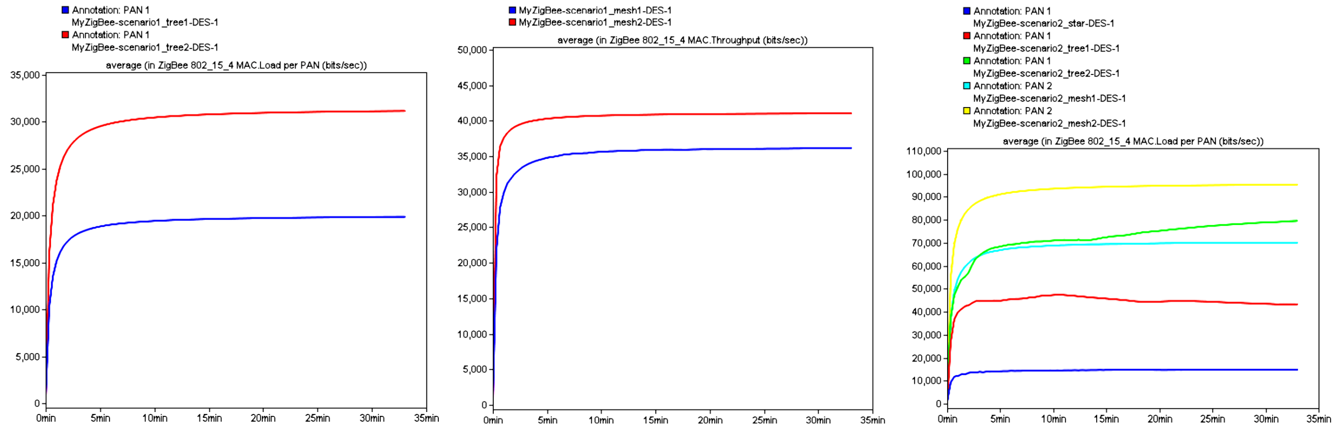
In order to investigate the reason why the tree topologies, tree2 in particular, perform as poorly as they have discussed, an inspection of the average number of hops for each network is taken. As can be seen in Fig. 5(b), the tree topologies exhibit a large number of hops in their routes from the source to the destination. This obviously account for the reason why they perform relatively poorer than they have done in the previous scenario.

In Fig. 5(c), it is observed that the mesh topologies have a higher throughput than the star and tree topologies, meanwhile the star topology provides the lowest throughput. This result is consistent with the one aforementioned in the previous scenario.

As expected, the results shown in Fig. 6, with a large density of routers in the mesh network, produce the highest MAC load per PAN. However, it is not consistent with the results from the previous scenario, i.e., the tree network case also with the larger density of routers produces a higher load than the other mesh network. One possible reason for this discrepancy is the additional number of hops that communication is requiring inside the network. The amount of extra computing time for routers can produce a much larger traffic load upon the network.

5. Conclusions

In this paper, we have investigated the performance of ZigBee protocol and IEE802.15.4 standard used in wireless sensor networks. The background information and advantages regarding ZigBee protocol have been presented together with an overview of the various layers of the protocol stack. Moreover, the OPNET Modeler simulation tool has been briefly discussed, along with its use in regard to the ZigBee wireless networks. The performance evaluation has been fulfilled by simulating two different scenarios under the three possible network topologies, where the tree and mesh cases further split into two separated cases each, to provide the simulations with different compositions of routers to end-devices ratio. The simulation results demonstrate that the mesh topology generally exhibits better performance than the other two types do. The star topology in particular performs the poorest among the three in all the simulations. An interesting finding is that the performance of tree topologies declines as the number of nodes increases in the network, due to congested traffic in the key nodes. Additionally, tree topologies cannot support a large density of routers in the network, as it will cause the nodes to involve increasing amounts of router hops in order to reach their destinations. In future work, we will find an optimal environment for WBSNs that can include a more thorough tuning of the



(a) Scenario 1 MAC load per PAN (tree) (b) Scenario 1 MAC load per PAN (mesh) (c) Scenario 2 MAC load per PAN.

Figure 6. Load per PAN results.

protocol parameters offered by OPNET. By tweaking these parameters, the networks can be designed to support optimal values of data throughput, frame delay, nodes, and others.

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